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Third-harmonic generation of a continuous-wave Ti:Sapphire laser in external resonant cavities

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An all-solid-state tunable continuous-wave (cw) laser operating near 272 nm with a bandwidth $\Gamma \approx 3$ MHz has been developed. The third harmonic of light from a single-cw Ti:Sapphire laser has been generated using two external enhancement cavities. An output power of 175 mW has been produced, corresponding to an overall conversion efficiency of 8%. © 2003 American Institute of Physics. [DOI: 10.1063/1.1584515]

All-solid-state tunable lasers are compact and reliable sources of high-power narrow-band coherent radiation. The applicability of these lasers, however, is limited as they mainly are operational in the red and infrared part of the spectrum. The goal of the present work was to construct an all-solid-state laser system operating at deep-UV wavelengths. Solid-state UV-laser systems producing the fourth harmonic of Nd:YVO₄ are commercially available. These systems are useful for certain applications, however, their wavelength (266 nm) cannot be tuned or scanned. The development of tunable UV lasers has been reported by the group of Hänsch.^{1,2} Bourzeix *et al.*³ reported on a fully solid-state UV-laser system, generating the fourth harmonic of a Ti:Sapphire laser. We report on third-harmonic generation of light from a tunable continuous-wave (cw) Ti:Sapphire (Ti:S) laser. This is achieved using two steps. First, second-harmonic light is produced using a LBO crystal inside an external enhancement cavity (EEC). Subsequently, this second-harmonic light is coupled into a second EEC, together with the fundamental light. Here, the sum frequency is generated in a BBO crystal. The power $P_{3\omega}$ generated in the sum-frequency process in the BBO crystal is given by

$$P_{3\omega} = \gamma P_{\omega} P_{2\omega}. \quad (1)$$

Here, P_{ω} and $P_{2\omega}$ are the incident fundamental and second-harmonic power, respectively, and γ is the nonlinear coefficient of the process. Resonantly enhancing both wavelengths inside a cavity leads to a high conversion efficiency for the sum-frequency process, expressed by

$$P_{3\omega} = \gamma A_{\omega} P_{\omega} A_{2\omega} P_{2\omega}, \quad (2)$$

where, A_{ω} and $A_{2\omega}$ are the cavity enhancement factors for the fundamental and second-harmonic waves and, now, P_{ω} and $P_{2\omega}$ are the respective powers of the light coupled into the cavity.

Sum-frequency generation with two diode lasers was realized by Sayama and Ohtsu.⁴ Doubly resonant sum-frequency light using two Nd:YAG lasers was generated by Kaneda and Kubota.⁵ Also, by combining a Ti:S and a diode laser, a narrow-band cw UV source with several tens of milliwatts output power was designed by Fujii *et al.*⁶ Third-

harmonic generation using only a single Ti:S laser was demonstrated by Sayama and Ohtsu,⁷ producing 8 nW of deep-UV radiation. In the present work, doubly resonant sum-frequency generation using a single Ti:S laser is demonstrated. The doubly resonant cavity is equipped with two Brewster plates to compensate for the dispersion in the crystal. The result is a compact narrow-band ($\Gamma \approx 3$ MHz), tunable cw laser capable of producing 175 mW of output power in the deep UV. A schematic of the setup is shown in Fig. 1.

Narrow-band 817 nm light from a tunable cw Ti:S laser (Coherent 899-21), which is pumped by a 10 W Spectra Physics Millennia-X laser at 532 nm, is separated into two beams using a 50%/50% beam splitter. The light of one of the beams is frequency doubled inside a bowtie-shaped EEC using a LBO nonlinear crystal cut at angles of $\theta = 90^\circ$, and $\phi = 29.8^\circ$ with respect to the optical axis. The crystal is cut at Brewster's angle for the fundamental wavelength. Mode matching of the Ti:S light into the EEC is performed by a thin lens L1. The cavity losses per roundtrip are close to 1%, therefore, the reflectivity of the input coupling mirror (M1) is chosen to be 99% to ensure impedance matching. This leads to a maximum coupling of 88% of the fundamental light into the EEC. The mirrors M3 and M4 have a reflectivity $>99.8\%$ and a radius of curvature of -75 mm to focus the beam inside the LBO crystal. The distance between M3 and M4 is optimized for maximum conversion efficiency. To

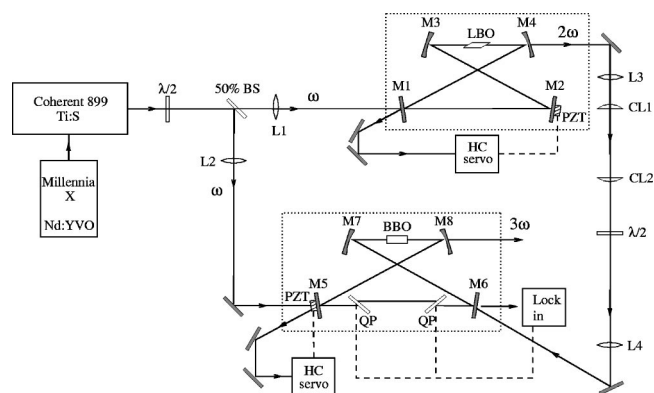


FIG. 1. Schematic of the setup for generation of the third harmonic of a Ti:S laser. BS: beamsplitter, QP: quartz plate, PZT: piezo, L: mode-matching lens, CL: cylindrical lens, M: mirror, and HC: Hänsch-Couillaud locking setup.

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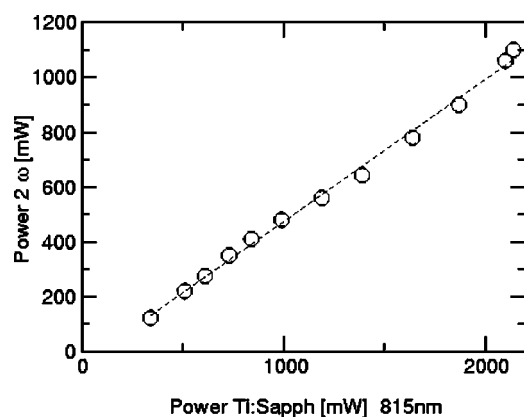


FIG. 2. Output power of the second harmonic as function of Ti:S power. The output power is measured after a dichroic mirror to separate residual fundamental and second harmonic.

keep the EEC in resonance, the cavity is locked to the fundamental wavelength using the Hänsch–Couillaud locking technique⁸ which supplies a feedback signal to the small (6 mm×2 mm) mirror M2 mounted on a piezoelectric crystal. The second-harmonic light is coupled out through M4 which is highly transparent (>97%) for the blue light at 408.5 nm.

From the full width at half maximum of the cavity etalon peaks and the free spectral range, a cavity finesse of about 530 is deduced. This leads to a cavity enhancement factor of 280, when conversion to second-harmonic wavelengths is not taken into account. From 1.00 W of input power at the fundamental wavelength 500 mW of usable second-harmonic power is measured behind the output coupler M4, a conversion efficiency of 50%. Taking into account the second-harmonic losses on the Brewster surface of the crystal (19.7%) and loss at M4 (2%) (Jurdik *et al.*),⁹ this corresponds to a total conversion efficiency of 63.5%. This is an extremely high conversion efficiency for cw frequency doubling of a Ti:S laser. Even higher conversion efficiencies (up to 85%) have been reported by the group of Kimble¹⁰ by doubling a Nd:YAlO₃ laser to 540 nm. The output power dependence on the fundamental input power of the frequency doubling system is shown in Fig. 2.

The second EEC is built up using doubly reflecting mirrors in order to enhance both the fundamental and the second harmonic. The small (6 mm diameter×2 mm thickness) mirror M5 mounted on a piezo is the input coupler for the fundamental, whereas M6 is the input coupler for the second harmonic. The round trip losses for the fundamental are close to 1%. For impedance matching, the reflectivity of M5 is chosen to be 99% for the fundamental and >99.8% for the second harmonic. On the other hand, round trip losses for the second harmonic are about 3%, hence M6 is chosen to be 97% reflective for the second harmonic and >99.8% for the fundamental. The mirrors M7 and M8, reflectivity >99.8% for both waves, have a radius of curvature of −75 mm, focusing both wavelengths inside a BBO crystal. Due to the spatial distribution of the resonator eigenmodes, the waists of both wavelengths will automatically overlap inside this crystal. This significantly simplifies the alignment procedure of the EEC. Note that the waist sizes of both waves will differ by a factor of the square root of their wavelengths. The BBO

crystal is cut at an angle of 42.2° and is antireflection coated for all three relevant wavelengths. The third-harmonic light is coupled out through M8, which is >95% transparent at 272 nm. For the fundamental light, the EEC has a finesse of approximately 310 leading to an enhancement of 98. The finesse for the second-harmonic light is measured to be 63, so the enhancement is 29.

The light sent into the EEC has to be properly mode matched in order to maximize the coupling. For the fundamental, this is achieved with mode matching lens L2. Mode matching the second harmonic is rather more complicated. Since the output of the second-harmonic EEC is divergent and elliptically shaped, a spherical lens L3 and two cylindrical lenses CL1 and CL2 are used to shape the beam profile. Lens L4 provides the mode matching for the second harmonic. For the fundamental and second harmonic, 88% and 75% incoupling is achieved, respectively.

At first glance, one would expect that when the cavity is resonant with the fundamental, it is also resonant with the second harmonic. However, this is not the case. Because of dispersion in BBO, the optical path lengths of the respective waves differ, giving rise to a shift from the resonance of the second harmonic when the cavity is locked to the fundamental. This problem is overcome by inserting two flat quartz plates in the cavity mounted on counter rotating galvos. To minimize losses, these plates are mounted under Brewster's angle which is almost the same for both waves.

Tuning the angle of these plates leads to an optical path length difference between both waves allowing for the compensation of the dispersion in BBO. This optical path length difference is calculated to be about 200 nm when the angle is tuned over 0.1° for two 2 mm thick plates. Thus, the cavity can be made resonant for both wavelengths: First, the cavity is locked to the fundamental using the Hänsch–Couillaud technique, subsequently, the second harmonic is also made resonant by slightly rotating the plates. This is achieved by a feedback signal applied to the galvos. The feedback signal is obtained by monitoring the rejected 408 nm light from M6. The galvo lock consists of a lock-in amplifier, used at a slow modulation frequency (80 Hz) with an additional dc current source added to find the closest resonance for the second harmonic. Fast disturbances (which are experienced by both wavelengths) are compensated by the fast Hänsch–Couillaud lock regulating the piezo, while the slowly varying dispersion is compensated for by the galvo plates. The resulting third-harmonic output as a function of Ti:S power is shown in Fig. 3.

The deep-UV light can be continuously scanned over 10 GHz at 272 nm. With the present optics set, the system can generate wavelengths in the range from 280 nm to 265 nm. Using other sets of optics and crystals, the entire Ti:S range can, in principle, be frequency tripled, generating wavelengths ranging from 235 nm up to 330 nm. Over many hours of operation, the output power of the system remains constant, implying that the optics and BBO crystal are not degrading under the influence of the generated UV light.

In summary, we have developed an efficient method to generate third-harmonic light of any cw single-mode laser. An external enhancement cavity is used to generate the second harmonic. A second high finesse enhancement cavity

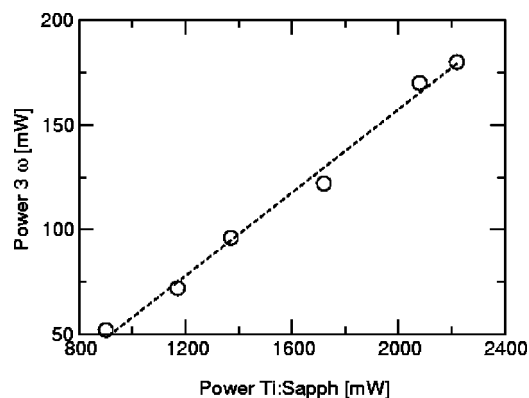


FIG. 3. Output power of the third harmonic as function of Ti:S power.

with dispersion compensating elements, enabling the locking of both the fundamental and the second-harmonic light of a Ti:S laser simultaneously, generates deep UV. Starting with 2.1 W light at the fundamental wavelength of 817 nm up to

175 mW of output power at 272 nm has been attained. The overall conversion efficiency of the process is 8%.

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